Introduction of the Ecological Connectivity Hypoxia Model: ECOHYM—Model Concept and Its Validation on a Study Applied to Tokyo Bay

Akio SOHMA

Environment, Natural Resources and Energy Division, Mizuho Information and Research Institute (MHIR), 2-3 Kanda-Nishiki-cho, Chiyoda-ku, Tokyo 101-8443, Japan

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Abstract—Environmental measures such as tidal flat creation, and nutrient load reduction from rivers are expected to result in hypoxia annihilation and lead to a bountiful ecosystem through an ecological chain response of estuaries comprised of benthic-pelagic or central bay-tidal flat ecosystems. The Ecological Connectivity Hypoxia Model (ECOHYM) was developed to demonstrate the mechanisms of ecological chain responses and its direction from two perspectives: “each biochemical and physical response, contributing to oxygen production/consumption (elemental approach)” and “the whole estuary, composed of mutual temporal-spatial linkage of benthic-pelagic or central bay-tidal flat ecosystems (holistic approach)”. The model was applied to Tokyo Bay and was calculated for a time frame of 100 years under seasonal forcing functions to achieve an annual periodical steady state. The calculated seasonal dynamics and daily/tidal dynamics were in good agreement with the observed data.

Keywords: coastal ecosystem, environmental restoration, hypoxia, tidal flat reproduction/restoration, nutrient load

INTRODUCTION

Ecological Connectivity Hypoxia Model: ECOHYM (“ZAPPAI” in Japanese) was newly developed as a science based communication tool on the deliberation how to recover the eutrophic estuaries. The estuaries in Japan such as Tokyo Bay, the water quality in Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Total Phosphorus (TP) has now recovered as the values of these dropped to lower compared to the worst time (Ministry of the Environment, 2006). However, the number of species and biomass of living organisms is still not recovered. The expected recovering direction for the estuaries now is not only to recover a “clean ocean in water quality”, but to recover a “bountiful ocean in biosphere”. Right side in Fig. 1 (Sohma and Sekiguchi, 2003) shows a hypothesis, the environmental improvement spiral (positive spiral) starting from the tidal flat creation/reproduction to the bountiful ocean through the decrease of red tide and the
hypoxia annihilation. The goal of the positive spiral may recover not only high/bountiful biodiversity, but recover the facility in nutrient transition from lower to higher trophic level, and higher utilizable potential of stored nutrients in the ocean. In contrast, left side in Fig. 1 shows a possibility for the reclamation/disappearance of tidal flats to drive the environmental deterioration spiral (negative spiral) toward “poverty ocean in biosphere”.

The above background derives the importance of the prediction/estimation of the goal of the ecological chain response shown as spirals in Fig. 1 on the deliberation how to recover the eutrophic estuaries. The ecological chain response in Fig. 1 is comprised of temporal and spatial interaction between the benthic-pelagic ecosystems and between the central bay-tidal flat areas, plus the interaction results from the internal ecosystem mechanisms in each system/area. Furthermore, hypoxia annihilation/generation, the essential driven force of the spirals, is mainly caused by the oxygen consumption/production at the sediment/sediment-water interface, and the mechanisms change precipitously on a micro-scale in the vertical direction (Canfield et al., 1993). Therefore, the required model to predict/estimate the goal of ecological chain response is to (1) integrate the central bay and tidal flat areas, (2) integrate the benthic and pelagic ecosystems, and (3) describe the micro-scale vertical ecological mechanisms in the benthic system. Within the ranges of our knowledge, ECOHYM is the first model to
achieve all items (1), (2), and (3) simultaneously.

The objective of this paper is to introduce the overview of the model construction, validation and one of the model outputs demonstrating the differences from bountiful ocean to clean ocean. The details introduced here were described in Sohma et al. (2005, 2008) and Sohma (2009).

**METHOD**

**Model description**

ECOHYM is composed of a hydrodynamics model and an ecological model for the benthic and pelagic systems. The ecological model is generalized to enable its application to both the central bay and tidal flat area. The physical processes in the pelagic system are calculated by the hydrodynamics model (Nakata et al., 1983; Sohma, 2009). The physical processes playing the transportation in the sediment or sediment-water interface such as molecular diffusion, irrigation, bioturbation and burial etc. (Berner, 1980; Boudreau and Jørgensen, 2001) are treated in the ecological model (Sohma, 2009). The biochemical processes/model variables treated in the ecological model are shown in Figs. 2 and 3. Mineralization
processes are divided into three categories: oxic, suboxic, and anoxic (Soetaert et al., 1996). Detritus are divided into three fractions: fast-labile, slow-labile and refractory organic matter (Multi-G model (Jørgensen, 1978)).

**Implementation**

A simulation was carried out to demonstrate the daily and seasonal dynamics of an average year of the existing Tokyo Bay. This simulation, “the control case”, is used for the validation and also is used for the reference on the estimation of ecological responses to the environmental measures by comparison with the simulation of the environmental measure applied scenarios. The prescribed functions (forcing functions) of the control cases were set as 1-year periodical functions. These functions were created based on the observed data from 1998 to 2002. The convergence state of this simulation demonstrated the dynamics with a 1-year period. For the horizontal spatial resolution, Tokyo Bay was divided with $2 \text{ km} \times 2 \text{ km}$ grid in the hydrodynamics model, and was divided into 26 zones (boxes) in the ecological model (Fig. 4). For the vertical spatial resolution, the pelagic system was sliced with 1–2 m intervals and the benthic system was sliced with 0.01–1.2 cm intervals (Fig. 4). For the time resolution, the notable time scale of dynamics in the ecosystems treated in the ECOHYM (i.e., (1) the pelagic...
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Fig. 4. Geographical description of Tokyo Bay (Calculated area, spatial resolution both in the vertical and horizontal directions, and coordinates \((i, j)\) on the model application).

Fig. 5. Seasonal variation of dissolved oxygen of the pelagic system (left, \((i, j) = (6, 4)\)) and of the benthic system (right, \((i, j) = (5, 4)\)) in the central bay area.

RESULT AND DISCUSSION

The model validation was conducted based on the comparison between the model outputs and the observed data, and the reproduction of temporal and spatial distribution of model variables and fluxes were checked. Here, the model outputs are the results of calculations in which the mutual interactions between benthic-
Fig. 6. Daily variations in dissolved oxygen of the pelagic system (left, \((i, j) = (8, 6)\)) and of the benthic system (right, \((i, j) = (8, 6)\)) in the tidal flat area.

Fig. 7. Early Tokyo Bay before relocations (left side), and its geographical description in the model (right side) i.e., tidal flat reproduction case. Hatching areas are additional/reproduced tidal flat areas in the model simulation.
pelagic or the central bay-tidal flat area are functional. For example, the calculated value of the nutrients around sediment-water interface results from the modeled mechanism/process, i.e., produced POM (detritus, phytoplankton and zooplankton) is sinking/sedimentated at the sea-floor, and the sedimented POM is mineralized, and produced nutrients in mineralization return to the pelagic system. Therefore, the forcing function/prescribed function of nutrients flux from the benthic to pelagic system is not set.

Figure 5 shows the comparison between monitoring data and model outputs about seasonal variation of dissolved oxygen (DO) in the central bay area, and Fig. 6 shows the comparison about daily variation of DO in the existing tidal flat area. The monitoring data in Fig. 5 was observed from 1998 to 2002, and the data in Fig. 6 was observed in 2003. Because of the model demonstrating an average year condition, model outputs for the comparison especially in Fig. 6, was used at the extracted period of 2–3 days when the phase relationship between the tidal level and the light intensity was almost the same as monitoring situation in the same month (August). As shown in Figs. 5 and 6, the DO dynamics in the model is almost good agreement with monitoring data. For the other model variables, the reproducibility were also the same level as DO. The detail results were introduced in Sohma et al. (2008) and Sohma (2009).

Further work by using the validated ECOHYM will focus on the differences from the effect of nutrient load reduction to tidal flat reproduction. Tokyo Bay on the scenario of reproduction of the early tidal flat reclaimed in the past (tidal flat reproduction case, (Fig. 7)) will be compared with Tokyo Bay on the scenarios of reduction of the nutrient. Ultimately, two scenarios will be evaluated and compared to the existing Tokyo Bay in terms of “water quality” (the anoxic water volume, detritus) and “biosphere” (the biomass of benthic fauna). The output will reveal the effects of the environmental measures of (1) tidal flat reproduction and (2) nutrient load reduction to keep/reproduce the high water quality (clean ocean) and high biosphere (bountiful ocean) as the result of an ecological chain reaction comprised of benthic-pelagic coupling and tidal-flat-central bay coupling which is described in ECOHYM.

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REFERENCES


A. Sohma (e-mail: sohmanzz@aol.com)